Mars 2020 Surface Mission Performance Analysis: Part 1. Science Exploration and Sol Type Modeling

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We developed a scenario-based mission performance model for the Mars 2020 Rover to help identify project-wide productivity and operability challenges and opportunities. We have modeled science exploration combining high-fidelity resource modeling, science strategies, and modular science activity scenarios. This is proving to be an effective way of incorporating science activities into an engineering-based performance model.

Nomenclature

BRS	=	Baseline Reference Scenario
MSL	=	Mars Science Laboratory
ROI	=	Region of Interest
Sol	=	Mars day
SSWG	=	Surface Scenario Working Group

I. Introduction

The Mars 2020 rover is NASA's upcoming rover to explore the surface of Mars, which leverages heritage design and hardware from the successful Mars Science Laboratory mission as much as possible while including new science instruments to seek the signs of ancient life on Mars. It has four mission objectives:

A. **Geologic History**
Carry out an integrated set of spatially-coordinated context and contact measurements to characterize the geology of the landing site
B. ***In Situ* Astrobiology**
Find and characterize ancient habitable environments, identify rocks with the highest chance of preserving signs of ancient Martian life if it were present, and within those environments, seek the signs of past life
C. **Select, Collect and Cache Samples**
Acquire and cache a suite of rigorously documented and returnable samples for possible future return to Earth
D. **Facilitate future human & robotic exploration** by helping fill in Strategic Knowledge Gaps (such as assessing local natural resources or potential hazards for future human explorers) and demonstrate new technologies and concepts of operation

To meet these objectives, the Mars 2020 rover (Fig. 1) carries seven scientific instruments, multiple engineering cameras, and a sample acquisition, processing, and caching system. The various payload elements work together to detect and study potential sampling targets with remote and in situ measurements; to observe the dust and atmospheric environment around the rover; and, to prepare for future human exploration by demonstrating in situ resource utilization technology (ISRU). The sample caching system includes a coring drill, collection tubes, and sealing mechanisms that will be used to collect core samples and deposit them on the surface of the planet for possible future return to Earth.

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Mars 2020 plans to launch from Cape Canaveral on a United Launch Alliance Atlas V-541 rocket during an opportunity between July and August of 2020, arriving at Mars in February of 2021. More information about the Mars 2020 Rover can be found at http://mars.nasa.gov/mars2020.

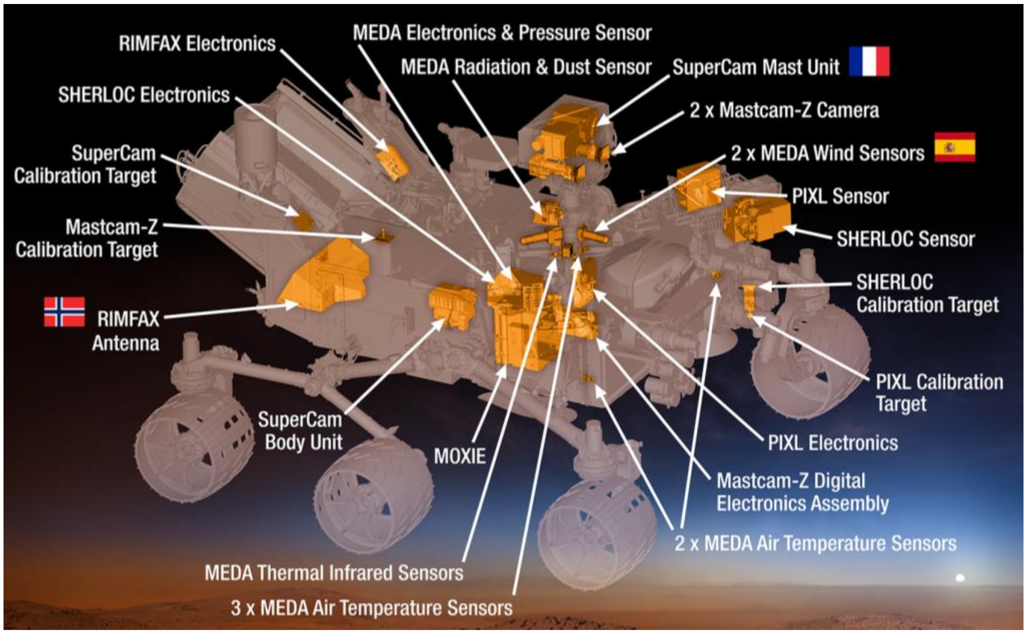

Figure 1. The Mars 2020 Rover Instrument Suite. *Locations of science payload hardware on the rover.*

In order to achieve mission success, the Mars 2020 rover must be capable of exploring the landing site, collecting enough data with the scientific payload to identify high science value cores, and collecting and caching 20 cores in prime mission. Based on experience with operating rovers on Mars (i.e., Sojourner, Spirit, Opportunity, and Curiosity), this means that the hardware and operations systems must be designed with a greater emphasis on operability than previous Mars rovers. We define operability as the ease with which a system operator can perform the assigned mission when the system is functioning as designed.

We developed a scenario-based mission performance model to help identify project-wide productivity and operability challenges and opportunities. This model gives focus to design and development efforts on vehicle operability, promotes a philosophical "imperative" for operability within the project, and cultivates mission/sol scenarios based on both science and engineering inputs. It also allows us to evaluate conceptual and technical trades for quantitative metrics on impacts to mission performance.

This is the first of a series of three papers describing the resulting mission performance model. In this part, we describe how we modeled science exploration for a prototypical landing site, to assist in evaluating technical trades during development, and for eight proposed landing sites on Mars, to assist in landing site selection. In part two (Ono et al[1]), we describe the new automated traversability analysis capabilities developed for the performance model including terrain classification, rock detection, digital elevation model generation, and optimal route planning, and apply them to the landing sites under consideration for the Mars 2020 rover. In part three (Lange et al[2]), we describe the full performance model, including thermal assessments and operational efficiency considerations, and present the full model results.

II. Scenario-Based Performance Modeling

A. Surface Scenario Working Group

The building blocks of our performance model are a series of surface scenarios that describe situations that the rover will encounter during nominal operations (driving to a new location, close examination of a rocky outcrop, etc). To describe what the rover operations team would want to do and how the rover would behave under these different scenarios, we assembled a Surface Scenario Working Group (SSWG) comprised of representatives from flight system engineers, science instrument development teams, mission system (operations) engineers, and the science leadership to bring together expertise on the rover hardware and software, instrument hardware, instrument science, project science, and surface operations. The SSWG was tasked with populating a series of plans to describe the set of rover activities that would occur in response to each scenario. Thus, understanding how the rover hardware, software, and operations designs come together can be used to understand the operability and performance of the mission. We have developed and maintained surface scenarios based on these cross-disciplinary inputs, and used them to assemble a model of mission performance.

B. Modeling Scientific Exploration

One challenge facing any model of spacecraft mission performance is how to realistically represent the resources (time, energy, data volume) required for science exploration many years before that exploration takes place, when the nature of planetary exploration is to make decisions on which actions to take based on the results found in the data previously collected.

Fortunately in the case of Mars 2020, the nature of the science and the constraints of the mission lend themselves to "campaign-based" planning, where science activities are concentrated in areas of interest identified strategically from orbit. The observations taken to study objectives A and B within the area are the same ones needed to select samples for objective C; once we understand the geological history of an area we will be able to determine which samples to take. This, combined with our experience operating MSL, allow us to modularize science exploration in a performance model.

In order to modularize science exploration strategies, we define the following terms:

1. *Region of Interest (ROI)* is a ~1 km x 1 km area of science interest, identified in orbital datasets.
2. *Campaign* is a ~100 m x 100 m area within the ROI selected for detailed science analysis, based on examining orbital data and concluding there is one or more interesting stratigraphic units present. Particularly enticing: contacts between multiple units, units containing spectral signatures of relevant minerals.
3. *Waypoint* is a parking location outside an ROI selected for sampling and limited contextual science
4. *Stratigraphic Unit* is a volume of rock that is mappable and distinct from another volume of rock. This concept from geology is used as a proxy for the geologic complexity of a study area; the more complex an area, the more data needs to be collected to understand it.
5. *Walkabout* is an exploration strategy involving collecting survey remote sensing data before picking locations for proximity science, akin to walking the outcrop in field geology. Used to great effect at Pahrump Hills by Mars Science Laboratory.

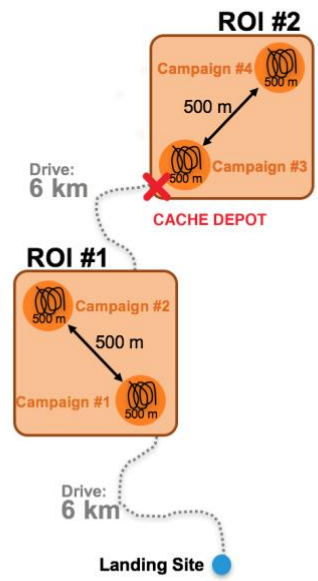

Figure 2. Baseline Reference Scenario. *Basic depiction of generalized Mars 2020 surface operations scenario.*

C. Baseline Reference Scenario

We have developed a "Baseline Reference Scenario" (BRS) as a representation of a prototypical surface mission for Mars 2020 to enable a systematic statistical evaluation of the resources required to accomplish science objectives within the prime mission. The BRS is used by the project during development to assess its likelihood of meeting mission objectives during the prime mission; it is fictitious but is informed by actual mission characteristics. It is not dictating precisely what is done during the surface mission, but is assisting the Mars 2020 project in assessing efficiency and productivity-related trades during development, as well as fleshing out capability requirements necessary to accomplish mission objectives.

The BRS mission is defined as follows (Figure 2):

> The project system shall have the capability to perform the following Baseline Reference Scenario (BRS) surface mission within 1.25 Mars years (836 sols), which includes the following:

- Conduct the investigations required to meet science objectives A and B and meet technology objective D
- Explore 2 distinct Regions Of Interest (ROI) of approximately 1 km x 1 km area.
- For each ROI:
  - 6 km of long traverse to reach
  - Conduct 2 science campaigns per ROI

    - Investigate 5 stratigraphic units per ROI
    - 1.5 km of local traverse to explore, consisting of:
        - 500 m “walkabout” driving per campaign
        - 500 m driving between campaigns
    - Acquire 9 cached samples per ROI, consisting of
        - 7 Rock and/or Regolith samples
        - 2 Witness Blanks
- Acquire [2] rock and/or regolith “waypoint” samples at any point during the mission
- Deposit the sample tubes at a single Cache Depot at a location near ROI #2

III. Model Building Blocks

A. Instrument Behavior
We build our model from the ground up, starting with instrument and subsystem models called *Operational Modes* or “*opmodes*” that represent discrete functions or behaviors and their associated resource utilization. Example opmodes might include “Power ON/Initialization”, “Acquire Image”, “Data collection”, “Data transfer”, or “Standby/Idle.” The Mars 2020 payload and engineering subsystems provide resource consumption estimates for basic Operational Modes. These modes are used to build typical use-cases, called *Activities*. In practice, Opmode & Activity definitions vary depending on how planning and operations is carried out for an individual instrument or subsystem. They take a simple set of parameters to define the intent of an operation and provide approximate resource utilization (Time/Duration, Power/Energy, Data Volume). Opmodes and Activities are encoded into a Mars 2020-adapted version of the MSL operations planning tool, called MSLICE.

B. Sol Type Scenarios
We move one layer up from activities into *Sol Type Scenarios (or Sol Types).* These are representative operational scenarios built from activities and used to inform overall mission performance. They contain the “critical path” science activities that are needed to complete essential operations towards a particular science or engineering objective, and are detailed enough to model rover resources of *Time/Duration*, *Power/Energy*, and *Data Volume*. They are modeled using MSLICE, which provides ops-like sol scenario planning and resource/constraint management as well as high-fidelity resource modeling.

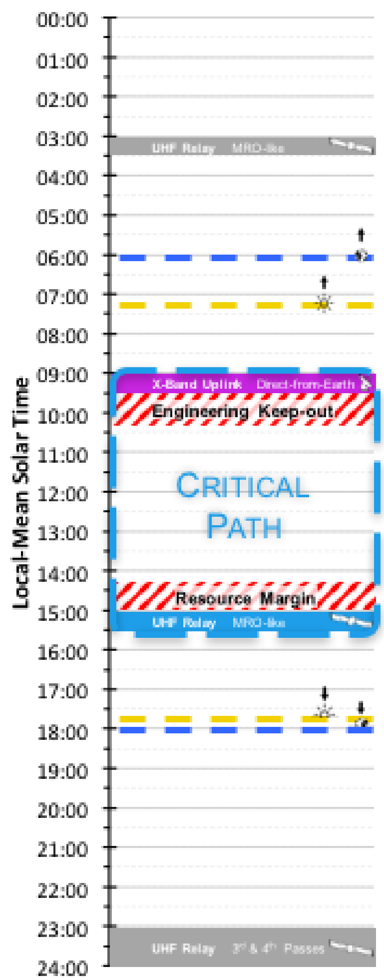

Figure 3. Sol Template. *Standard activities included in every sol within each sol type scenario.*

Each Sol Type is built in the *Sol Template*, which represents a generic sol of rover operations on Mars (Fig. 3). 09:30 LMST is the end of HGA X-Band uplink and the start of daily rover operations. The sol template includes an engineering keepout zone at the beginning of the critical path for daily engineering activities that require ground-in-the-loop priority, and includes the traditional x-band “beep.” We keep a resource margin of time and power at the end of the critical path against opmode & activity design maturity, per JPL design principles. Also included is a resource allocation for 4 daily UHF passes, where data collected by the rover is sent to an orbiter and then relayed to Earth. Two passes are arbitrarily timed because of walking relay windows.

Every Sol Type must keep within resource constraints (fitting within time allocation, being energy-neutral or energy-positive, and returning the necessary “decisional” data to make decisions for planning the next sol). In addition, a Sol Type must avoid too much complexity (e.g., over-optimization, parallel activities, etc) that would lead to it being difficult to implement by an operations team. A Sol Type may take multiple sols to accomplish its objective.

The Sol Types were developed within the SSWG (see previous section). The objective of a particular sol type was determined, and then the instrument and subsystem representatives determined which activities best described the data needed to achieve that objective. This was an iterative process as the instrument teams used feedback on resource constraints to improve the operability of their instruments during development. Sol types were reviewed and revised as updates to hardware capabilities were identified by the development teams.

In Tables 1 and 2, each sol type is listed along with its objectives, the major payload elements involved, and the resources needed to complete the sol type.

Sol Type	Sol Type Objective	# of Sols	Payloads	Functional Area
Survey Remote Sensing	Broad survey of new locale to find targets of interest for follow-up science	1	MCZ, SuperCam, MEDA	Remote Science
Workspace Remote Sensing	Observations of the workspace	1	MCZ, SuperCam, MEDA	Remote Science
Natural Proximity Science	Examine two targets within workspace	1	PIXL, SHERLOC, WATSON, MEDA	Robotic Arm Science
Abraded Proximity Science	Abrade and examine one target within workspace	2	PIXL, SHERLOC, WATSON, MEDA	Robotic Arm Science
Long Drive	Optimized for longest drive within resource envelope	1	RIMFAX, MEDA, EECAM	Mobility
Medium Drive	Drive + 1 hr science block	1	RIMFAX, MEDA, EECAM	Mobility
Short Drive	30 m drive + opportunistic science block	1	RIMFAX, MEDA, EECAM	Mobility
Precision Approach	Final approach (within 10 m) to outcrop + opportunistic science block	1	RIMFAX, MEDA, EECAM	Mobility
Precision Approach with Go and Hover	Final approach + arm unstow and workplace imaging + opportunistic science block	1	RIMFAX, MEDA, EECAM, WATSON	Mobility/Robotic Arm Science
ISRU	Run Full MOXIE O2 Cycle	1	MOXIE, MEDA	Remote Science
MEDA-dedicated	Run MEDA intensive for 1 sol	1	MEDA	Remote Science
Sample acquisition & borehole science	Collect a sample and perform documentary science on cuttings, borehole	3	MCZ, SuperCam, PIXL, SHERLOC, WATSON, EECAM, MEDA	Robotic Arm Science/SCS

Table 1. Sol type scenarios and objectives

An example of a sol type scenario is the Abraded Proximity Science Sol Type (Fig. 4). This sol type occurs when the rover operations team wishes to abrade (or smooth) a location of scientific value within the robotic arm workspace, and to examine that surface with the instruments mounted on the arm turret, SHERLOC (a fine-scale imager and mineralogy instrument) and PIXL (a fine-scale elemental chemistry instrument). In this scenario, we assume that the rover is positioned such that it is safe to use the arm.

In Sol N, the rover wakes up at the start of the day and performs engineering maintenance activities. The two mast-mounted instruments (Mastcam-Z, a stereo imager, and SuperCam, which assesses surface composition), will measure the surface target. Then the rover will prepare the surface for proximity science studies using the abrasion bit. The arm will move out of the way for post-abrasion observations by the Mastcam-Z camera, and then the SHERLOC imager at the end of the arm will take higher-resolution post-abrasion observations. This is followed by SHERLOC spectral observations and a quick mosaic by the PIXL micro-context camera to get an initial assessment of the surface, in order to guide the decisions for the following day. The critical data is relayed to the waiting operations team via an orbiter overflight. The rover then shuts down for the night, occasionally waking up for an orbiter relay pass.

On Sol N+1, the rover again wakes up at the start of the day and performs engineering maintenance activities. SHERLOC spectrometer performs follow-up observations on the abraded surface, and SuperCam performs post-abrasion observations as well. PIXL creates an elemental abundance map of a portion of the abraded surface. The critical data is relayed to the waiting operations team via an orbiter overflight, and then PIXL continues taking measurements throughout the night while the rover sleeps. The rover wakes up for overnight relay passes. Throughout both sols, MEDA collects information on atmospheric temperature, pressure, opacity, and wind speed.

Sol Type	# of Sols	Minimum State of Charge	Decisional Data Volume	Additional Time/Power Available?
Survey Remote Sensing	1	66%	60 Mbit	Power and Time inside the critical path
Workspace Remote Sensing	1	67%	70 Mbit	Power and Time inside the critical path
Natural Proximity Science	1	59%	90 Mbit	No
Abraded Proximity Science	2	65%	Sol 1: 60 Mbit Sol 2: 60 Mbit	No
Long Drive	1	50%	60 Mbit	No
Medium Drive	1	60%	50 Mbit	Power and Time inside the critical path
Short Drive	1	60%	50 Mbit	Power and Time inside the critical path
Precision Approach	1	65%	100 Mbit	Power and Time inside the critical path
Precision Approach with Go and Hover	1	60%	100 Mbit	Power and Time inside the critical path
ISRU	1	40%	10 Mbit	No power – all allocated to MOXIE
Sample acquisition & borehole science	3	40%	Sol 1: 55 Mbit Sol 2: 40 Mbit	No

Table 2. Sol type scenarios and resource usage

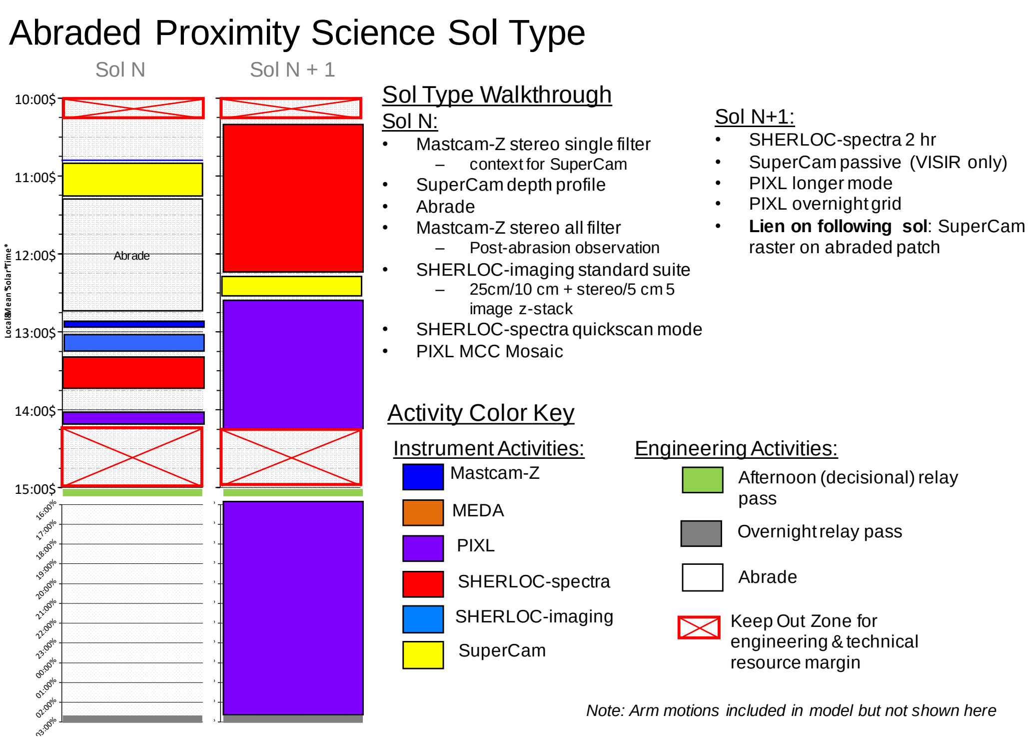

Fig. 4. Abraded Proximity Science sol type scenario. *A two-sol scenario is required to complete all activities necessary to accomplish the science objectives of the abraded proximity science sol type.*

This sol type scenario takes two sols to complete for two fundamental reasons. First, the act of abrading a target changes the relief of the surface, which means that the robotic operations team needs to see the resulting surface to determine how close they can position the turret instruments for optimal follow-up observations. Second, the science operations team needs the data collected on the first sol in order to determine the details of the instrument settings on the second sol. This is an average case: occasionally we will want to take an additional sol for further PIXL/SHERLOC observations.

IV. Assembling the Science Model

We model the science exploration portion of the Mars 2020 BRS surface mission by combining together Sol Types according to ratios determined after researching MSL science campaign examples, comparing to terrestrial fieldwork experience, and interpreting M2020 mission objectives. This allows for estimation of overall mission performance for values such as mission duration, sols-per-sample, science campaign execution, and so forth.

In order to represent the science observations associated with Objectives A (geological history and habitability), B (biosignatures), and C (scientifically-selected samples) we need to include the observations to understand the campaign area from the surface ("Area-dependent factors" based on the number of campaigns) as well as observations to understand the stratigraphic units within the campaign ("Geological diversity-dependent factors" based on number of units). The Sol Type ratios we use to describe science exploration within the mission performance model are:

Area-dependent factors (per Campaign)
- 5 instances of remote sensing sol types per Campaign

Diversity-dependent factors (per unit)
- 4 instances remote sensing per unit
- 2 instances natural proximity science per unit (2 targets/instance)
- 4 instances abraded proximity science per unit (1 target/instance)
- 5 precision approach "parking spots" per Unit (10-meter bump)
  - 50% followed by instance of workspace Remote Sensing
  - 50% go & hover, no workspace Remote Sensing sol
- Remainder of ROI traverse distance Blind-drive only (30-meter drives)

Additional sampling science
- 1 additional instance natural proximity science per sample
- 1 additional "parking spot" per sample
  - 50% followed by instance of workspace Remote Sensing
  - 50% go & hover, no workspace Remote Sensing sol

Rock Waypoint Sampling
- 2 instances of abraded proximity science per waypoint
- 1 instance of remote sensing per waypoint

Regolith Waypoint Sampling
- 2 instances of natural proximity science per waypoint
- 1 mobility "scuff" (modeled as Blind drive for now)
- 1 instance of remote sensing per waypoint

A. An Example Campaign

We can examine the reasonableness of these ratios by running the science exploration model for an example campaign, seeing the numbers of each type of sol type that are produced, and assessing if that is a reasonable amount of sols spent on science to understand this campaign area.

For a campaign with three stratigraphic units where we expect to collect four samples, we result in the numbers and distribution of sol types in Table 3. This adds up to a campaign duration of ~90 sols, which we consider to be a reasonable number. To assess if this is a reasonable number, we can string sol type scenarios together in a calendar-like fashion, creating a sol path. Drawing upon the walkabout concept, we outline a series of sol paths for each loop of the walkabout (remote sensing, proximity science, and sampling), as seen in Fig. 5.

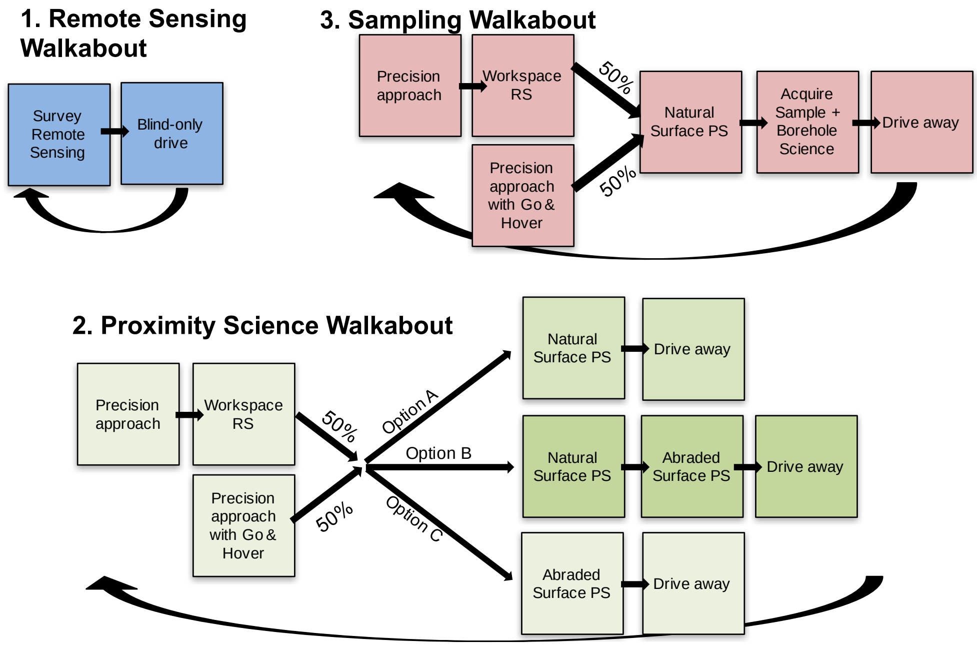

Figure 5. Walkabout Scenario Sol Paths. *For the proximity science walkabout in this example, we assembled the path using the options as follows: Option A=3 times, Option B=3 times, Option C=9 times.*

We can now assemble our complete sol path for this example campaign (see Fig. 6 and 7). We can see that our science exploration model has resulted in a surface campaign that is rich with scientific observations, and should be sufficient to accomplish the measurements needed to understand the geological setting (Objective A), assess the potential for astrobiology (Objective B), scientifically select valuable samples for collection (Objective C), and run the ISRU occasionally (Objective D).

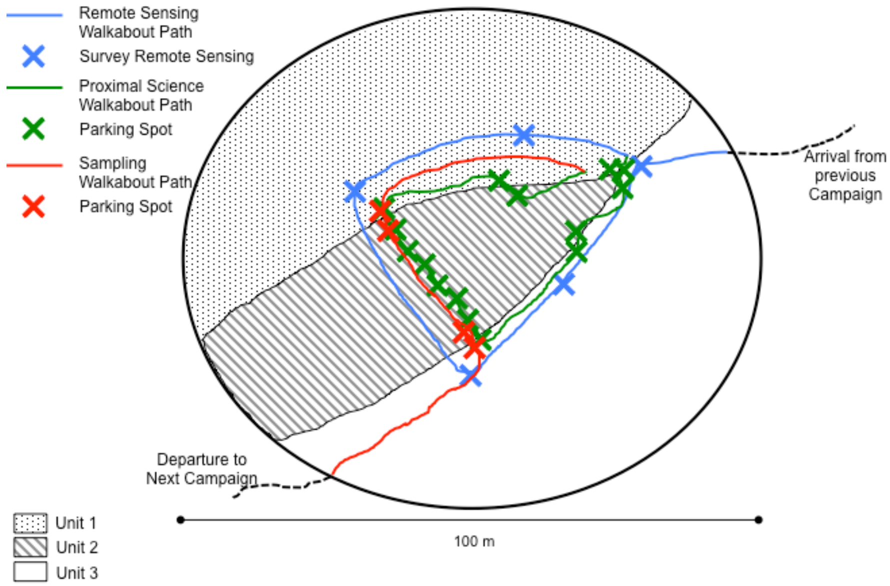

Figure 6. An example campaign. *This campaign contains three stratigraphic units, and is explored via three walkabouts to acquire the observations needed for rover science objectives A, B, C, and D. The number of drives and parking spots is determined by the science exploration model.*

Time increases across and down, like a calendar

Blind-only drive	Survey RS	Blind-only drive	Survey RS	Blind-only drive	Survey RS	Blind-only drive
Survey RS	Blind-only drive	Survey RS	Blind-only drive	Go & Hover	Natural Surface	Precision approach
Work space RS	Natural Surface	Abraded Surface 1	Abraded Surface 2	Precision approach	Work space RS	Abraded Surface 1
Abraded Surface 2	Blind-only drive	Go & Hover	Abraded Surface 1	Abraded Surface 2	Precision approach	Work space RS
Natural Surface	Blind-only drive	Precision approach	Work space RS	Abraded Surface 1	Abraded Surface 2	Go & Hover
Abraded Surface 1	Abraded Surface 2	Go & Hover	Natural Surface	Abraded Surface 1	Abraded Surface 2	Precision approach
Work space RS	Abraded Surface 1	Abraded Surface 2	Precision approach	Work space RS	Natural Surface	Abraded Surface 1

Figure 7a. First half of High-level sol path for our example campaign.

Time increases across and down, like a calendar

Abraded Surface 2	Go & Hover	Abraded surface 1	Abraded surface 2	Go & Hover	Abraded surface 1	Abraded surface 2
Precision approach	Work space RS	Natural Surface	Blind-only drive	Go & Hover	Abraded surface 1	Abraded surface 2
Precision approach	Work space RS	Abraded surface 1	Abraded surface 2	Blind-only drive	Go & Hover	Natural Surface
Acquire Sample + Borehole 1	Acquire Sample + Borehole 2	Acquire Sample + Borehole 3	Precision approach	Work space RS	Natural Surface	Acquire Sample + Borehole 1
Acquire Sample + Borehole 2	Acquire Sample + Borehole 3	Blind-only drive	Precision approach	Work space RS	Natural Surface	Acquire Sample + Borehole 1
Acquire Sample + Borehole 2	Acquire Sample + Borehole 3	Go & Hover	Natural Surface	Acquire Sample + Borehole 1	Acquire Sample + Borehole 2	Acquire Sample + Borehole 3

Total: 91 days

Notes:
- Does not include other factors in the model, such as ops efficiency, SRAP, margin, lost sols

Figure 7b. Second half of high-level sol path for our example campaign.

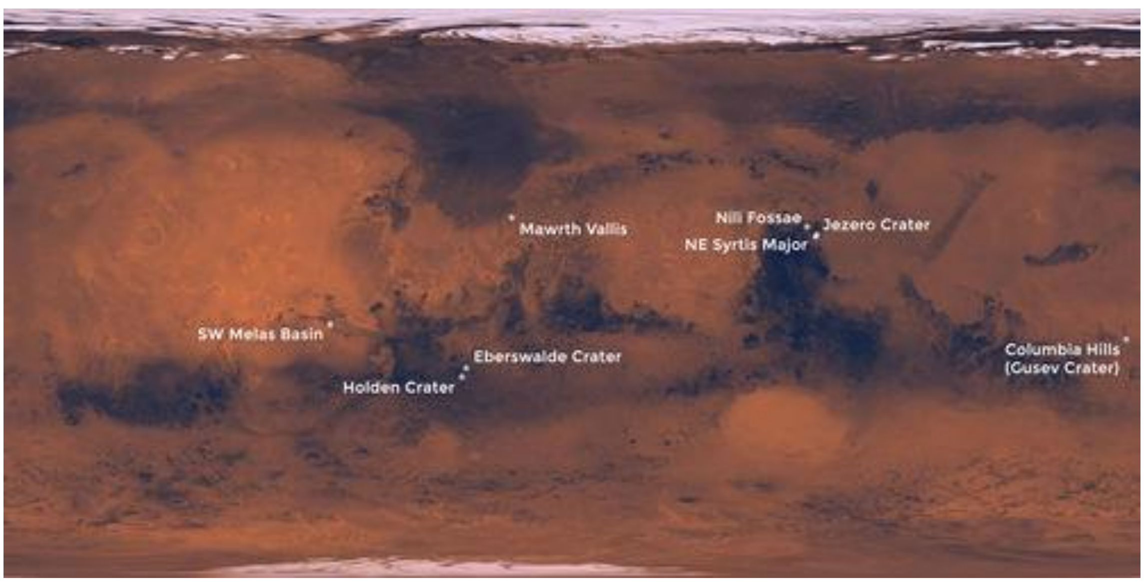

Figure 8. Potential Landing Sites. *Locations of 8 potential landing sites for the Mars 2020 Rover under consideration during the Third Landing Site Workshop in February 2017.*

V. Landing Site Specific Science Exploration Modeling

Between August 2015 and February 2017, eight candidate landing sites for Mars 2020 were under consideration by the project and the Mars scientific community (Fig. 8). As part of the project analysis, the mission performance model was run on each site, including the science exploration model. Science exploration objectives and approach can vary from site-to-site, so the Project collaborated with landing site proposers to define and prioritize potential ROIs, campaigns, and waypoints for detailed science exploration within each landing site (Table 4). We worked to make "science value" level across all sites, but some sites are more complex than others when it comes to meeting the scientific exploration objectives that make these locations attractive to the science community. The ROI locations from this analysis also provide mobility path planning destinations, which gives overall traverse distance characteristics for each site (see part 2, Ono et al, 2017[1]).

Total Campaigns	Total Units	ROI Samples	Waypoint Samples	Witness Samples	Total Samples	Total ROI Distance (m)	
6	6	14	2	4	20	3800	Eberswalde
3	8	13	3	4	20	1600	Columbia Hills
4	10	14	2	4	20	3100	Holden
4	12	13	3	4	20	2700	Jezero
4	8	13	3	4	20	2600	Mawrth
4	8	12	4	4	20	2400	NE Syrtis
4	10	12	4	4	20	3000	Nili
4	10	14	2	4	20	2600	SW Melas
4	10	14	2	4	20	3000	BRS

Table 4. Science exploration model inputs for each candidate landing site

The results of this analysis can be found in Fig. 9. One of the landing sites (Jezero Crater) is more complex (e.g., greater number of units) and thus will need more time to collect enough science data to achieve the Mars 2020 science objectives. Note that this the science-only mission performance for 1.25 MY missions. It does not consider the traversability of the landing site (see part two, Ono et al, 2017[1]) nor the thermal environment of the landing site (see part three, Lange et al, 2017[2]).

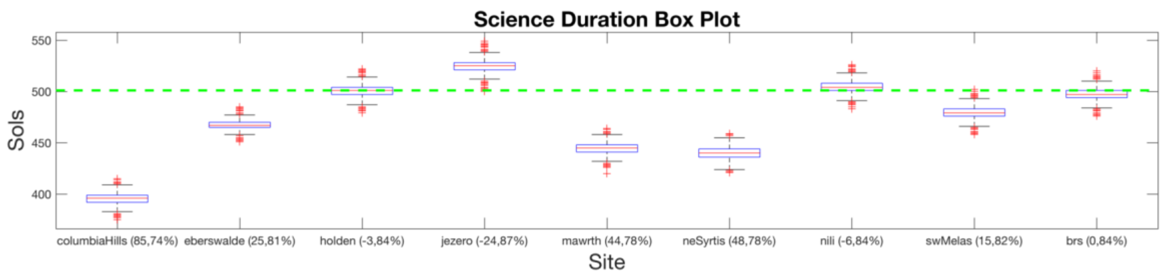

Figure 9. Science exploration model results for each candidate landing site, compared to the baseline reference scenario.

VI. Conclusion

This technique of modeling science exploration combining high-fidelity resource modeling, science strategies, and modular scenarios is proving to be an effective way of incorporating science activities into an engineering performance model, and allows for operability and efficiency trades to be made during mission development.

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